3.—THE CONTACT BETWEEN THE GRANITIC ROCKS AND THE CARDUP SERIES AT ARMADALE.

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CONTENTS.

I.—INTRODUCTION.

The Darling Scarp (Jutson, 1934, p. 84) is a prominent physiographic feature of the country near Perth. It forms the western edge of the Western Australian Pre-Cambrian plateau, which stands about 1,000 feet above sea level, and which is made up mainly of granitic rocks with later doleritic intrusions. West from this scarp and extending to the coast is a comparatively flat coastal plain underlain by Cainozoic and Recent sediments and bordered along the coast by Recent sand dunes (Clarke, 1926).

On the western face of the scarp a series of steeply dipping slaty sediments which form a narrow band between the granitic rocks and the younger horizontal sediments of the coastal plain is developed in a number of places extending from Gosnells and Kelmscott in the north to at least as far south as Mundijong (Honman, 1912 and Esson, 1927). These slaty sediments have been referred to as the Cardup Series (Clarke, 1930, table, p. 187) and they are considered by both Clarke (loc. cit.) and Forman (1937, p. xxiv.-xxv.) to be contemporaneous with the Jimperding Series of Yilgarn (early Pre-Cambrian) age and therefore older than the granites and granitic gneisses of the Darling Range. Forman (1937, p. xxiv.) says that the structures in the Cardup Series between Kelmscott and Mundijong conform to the local structures in the adjoining gneisses and suggests that the gneisses are, in part, of the same age as the Cardup Series and owe their origin to the alteration of these sedimentary rocks by a granitic magma, either the same or an earlier magma to that which provided the massive granites of the Darling Range.

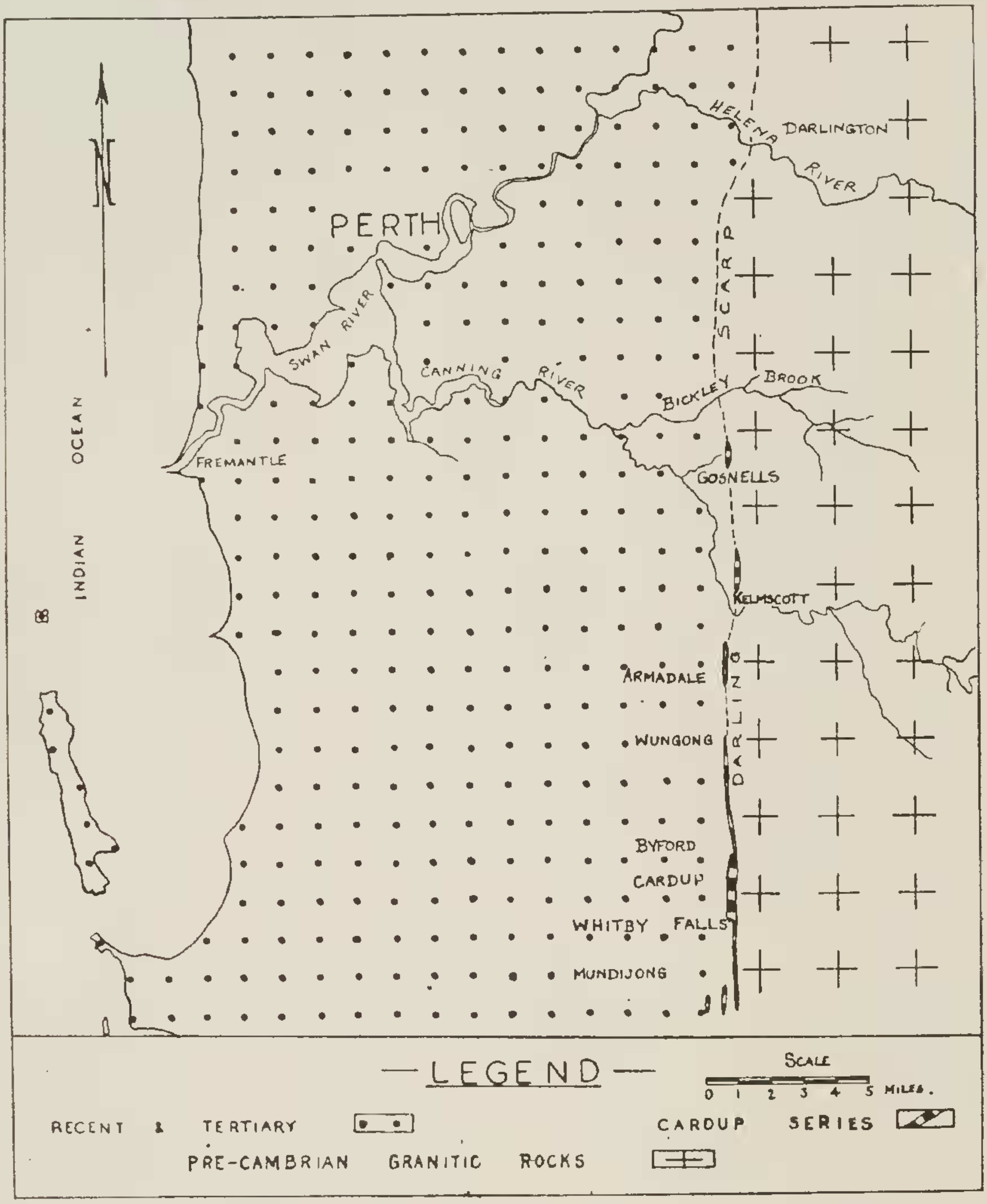

Figure 1.

Geological sketch map of the country between Upper Swan and Mundijong and extending to the coast, showing localities mentioned in the text.

The present investigation was undertaken to determine if possible, whether this "granitisation" of the Cardup Series has actually taken place and to determine the relative age of the granitic gneisses and the slaty sediments of the Cardup Series. I am indebted to Mr. H. A. Ellis, Assistant Government Geologist of Western Australia, for suggesting that the possibility of granitisation of the Cardup sediments should be investigated.

The area examined in detail is situated on the Darling Scarp just south of the Narrogin Inn at Armadale, some 19 miles south-east from Perth (fig. 1). It measures only about ½ mile x ¾ mile, but outcrops are fairly abundant; fresh examples of both the sedimentary and granitic rocks are obtainable in the two quarries; and most of the rock types that have been noted elsewhere in the vicinity of the Darling Scarp are developed. This small area is therefore perhaps the most suitable place to commence a detailed study of the petrology and structure of the Scarp.

II. GEOLOGY.

(1) *The field distribution and age relations of the rocks.*

The eastern half of the area (Plate 1) is occupied by granitic gneisses in which there appear to be two distinct groups:

(i) The fine banded granitic gneisses forming the western edge of the granitic rocks. These form a band approximately 8 chains wide which trends 350° parallel to the contact of the granitic rocks and the Cardup sediments. The foliation in these gneisses strikes parallel to the gneiss-sediment contact and dips at 50° to 60° towards the east. These gneisses appear to be uniform and granitic in character throughout the whole band and nowhere were they found to carry xenolithic inclusions as do the hybrid gneisses farther to the east. Contortion of the gneissic banding is visible in places and in other places the banding may be almost invisible, the rocks there being indistinguishable from massive granites.

(ii) The hybrid gneisses which occupy all the area to the east of (i). These gneisses have a general strike of 25° and dip at angles of 40° to 60° to the east. They are best exposed in the Roads Board quarry in the north-eastern corner of the area.

The rocks in this quarry and their field relations will be described in some detail as it is clear here that there have been two distinct periods of granite intrusion, the evidence for which periods of granite intrusion in the Pre-Cambrian history of Western Australia has been accumulating during recent years (Miles, 1938, p. 36; Prider, 1938, p. 101, and 1939, p. 93; Ellis, 1939, p. 91).

The rocks developed and their field relations as seen in this quarry are:—

(a) Dark coloured biotite-epidote-hornblende hornfelses. These rocks are well developed on the southern wall of the quarry where they appear to form a flat lying band in a more granitic gneiss (b) which is crowded with xenoliths of this dark green hornfels. On the western wall of the quarry, just inside the entrance the biotite-epidote-hornblende hornfels occurs as numerous xenoliths up to 12 inches diameter accompanied by xenoliths of coarsely granular quartz (? quartzite) in a hybridised gneiss (b) (plate 2, fig. 1). This dark coloured hornfels (together with the quartz xenoliths) is clearly the oldest rock exposed in the quarry.

(b) Mesocratic hybrid augen gneisses. These form the base in which the xenoliths (described above) occur. They are well banded coarsely granular rocks, often exhibiting augen structures and are composed of quartz and felspar with thin lenticular dark coloured bands, which under the microscope are seen to be remnants of the biotite-epidote-hornblende hornfels and they appear to have resulted from the intrusion of granitic material into the biotite-epidote-hornblende rocks (see under petrology)—this rock thus represents the first period of granite intrusion (or granitisation). The best exposures of this rock are to be seen on both faces of the quarry just inside the entrance.

(c) Aplogranite. This rock, a leucocratic medium grained massive to very slightly gneissic granite with little or no ferro-magnesian constituents (with the exception of occasional biotite-epidote-hornblends clots picked up from the older rocks) is exposed over the greater part of the north-west and south-west walls of the quarry. It is clearly intrusive into the hybrid gneiss (b above) which, in places, occurs in the form of large irregularly oriented angular blocks suspended in the aplogranite which truncates the banding of the gneiss. The aplogranite is therefore definitely a later intrusion and represents the second period of granite intrusion.

(d) Dolerite. A post-aplogranite dolerite dyke is present near the north-eastern edge of the main quarry and is younger than all the above mentioned rocks which it cuts indiscriminately.

The exposures in this Roads Board quarry therefore give us considerable information regarding the age relations within the eastern group of gneisses of the Armadale area. The sequence is:—

Younger.	(4)	Dolerite dykes.
	(3)	Massive aplogranites.
	(2)	Hybrid augen gneisses.
Older.	(1)	Biotite-epidote-hornblende hornfelses and quartz xenoliths in the hybrid gneiss.

The field relations of the eastern group of gneisses to the western group are unknown. The eastern group shows the highest degree of hybridisation in the north-eastern part of the area but continue to be hybridised to some extent even at the south-eastern corner.

A number of well defined quartz veins which all have the same strike of approximately 305° and dips of 85° to 90° to the north-east are seen to cut through both the hybrid gneisses and the fine banded granitic gneisses. Two of these quartz veins (one of them some three or four feet wide) were traced right to the contact of the gneiss and the Cardup sediments but careful search shows that they do not extend beyond the contact and they appear to be of pre-Cardup age, probably representing an ultra-acid differentiate from the aplogranite magma. If this be the case the position of the Cardup Series in the Pre-Cambrian succession is fixed as younger than the granite but older than the quartz dolerite intrusions, which are considered by all observers to have taken place during late Pre-Cambrian times and which represent the youngest rocks in the Western Australian Pre-Cambrian shield. (Clarke, 1930; Forman, 1937.)

Quartz veins striking almost due north also occur but are not so well developed as those which strike north-west. The main member of the north striking group forms a prominent quartz blow on the north side of the Bedfordale Road near the southern boundary of the area (Plate 1). The "blow" is lenticular and appears to be surrounded by granitic gneiss. There are some small mineworkings on this blow in the form of a shallow incline shaft and an adit—observations made on the white quartz from the surface and the softer more micaceous rock below are described in the section on petrology. The surface quartz in places shows the presence of irregular strings of fine grained dark coloured rock, not unlike slate in appearance. Extending north from this quartz blow along the same strike there is a band where no outcrops are to be found but where occasional small boulders of the dark coloured fine grained slaty rock are noticeable. There is no doubt that this band of slaty rock extends north to at least as far as the centre of the mapped area (Plate 1). Further consideration of the origin of this rock is given in the petrology section of this paper.

The western strip of the area is occupied by the sedimentary rocks of the Cardup Series. These rocks strike parallel to the granite gneiss-sediment contact and dip (on the average) 60° to the west. Traversing this series in a westerly direction from the contact the succession is quartzite (with fine cherty bands), sandy slate, fine white slate, dark greyish to black carbonaceous slate, and fine white slate (these rocks are referred to as slates but they are little more than shales with a very poorly developed fracture cleavage). A few examples of graded bedding were noted in the section exposed along the Bedfordale Road at the south end of the area and readings taken here indicate that the older beds lie to the east, i.e., that the sequence is normal and not overturned. The actual contact with the granitic gneisses is only visible in one place (on the road at the south end of the area) but it can be fixed within several yards over the remainder of the area and the succession of beds is everywhere the same. The Cardup sediments are best exposed in the quarry at the south-western corner of the area (where the slates have been quarried for brickmaking) and are seen to be slightly drag-folded and traversed by numerous minor faults with displacements of several inches. The nature of this minor faulting and drag-folding will be more fully described in the following section dealing with the structure of the area.

The Cardup Series is cut by a number of doleritic dykes which may be traced from the granitic rocks into the neighbouring sediments. From the geological plan of the area (Plate 1) it will be seen that the dolerite dykes appear to have been intruded along a definite set of fractures which extend from the granitic rocks into the sediments. In one place (on the west wall of the slate quarry) greenstone has been intruded in the form of a sill in the sediments and has produced slight contact alteration of the slaty rocks. No such contact effects were noticed along the gneiss-sediment contact.

From the field occurrence the chronological order of the rocks exposed in the area mapped appears to be:—

Youngest. (8) Minute barite veinlets in the dolerite on the east face of the slate quarry.
(7) Dolerite dykes.
(6) Epidiorite sill in Cardup slates.
(5) Cardup sediments (quartzites, sandy slate, white slates, black carbonaceous slates, white slates).
(4) Quartz veins in gneisses.
(3) Aplogranite intrusions. } Fine banded granitic gneisses, exact relation to (2) and (3) unknown.
(2) Hybrid augen gneisses.
Oldest. (1) Biotite-epidote-hornblende hornfels and quartz (? quartzite) xenoliths in the hybrid augen gneisses.

(2) *The Geological Structure.*

Mapping of all of the available minor structures of the exposed rocks has yielded a considerable amount of information regarding the structure of the area (and of the Darling Scarp generally). The hybridised gneisses of the eastern section show minor folding in a number of places but no constancy in the orientation of these structures could be found, as will be readily understood after an examination of the exposures in the Roads Board quarry, where the gneisses are seen to be in xenolithic blocks, irregularly oriented, in the intrusive aplogranite. No attempts have therefore been made to interpret the minor drag-folded structures seen in these rocks.

The drag-folds in the fine banded granitic gneisses are more constant in character and indicate that the easterly dipping rocks of this band form the eastern limb of a normal anticline with a pitch to the south varying from 0° to 30°. All outcrops in this band were carefully examined for these drag-folded structures and wherever visible they invariably indicated that this band formed the east limb of a normal anticline.

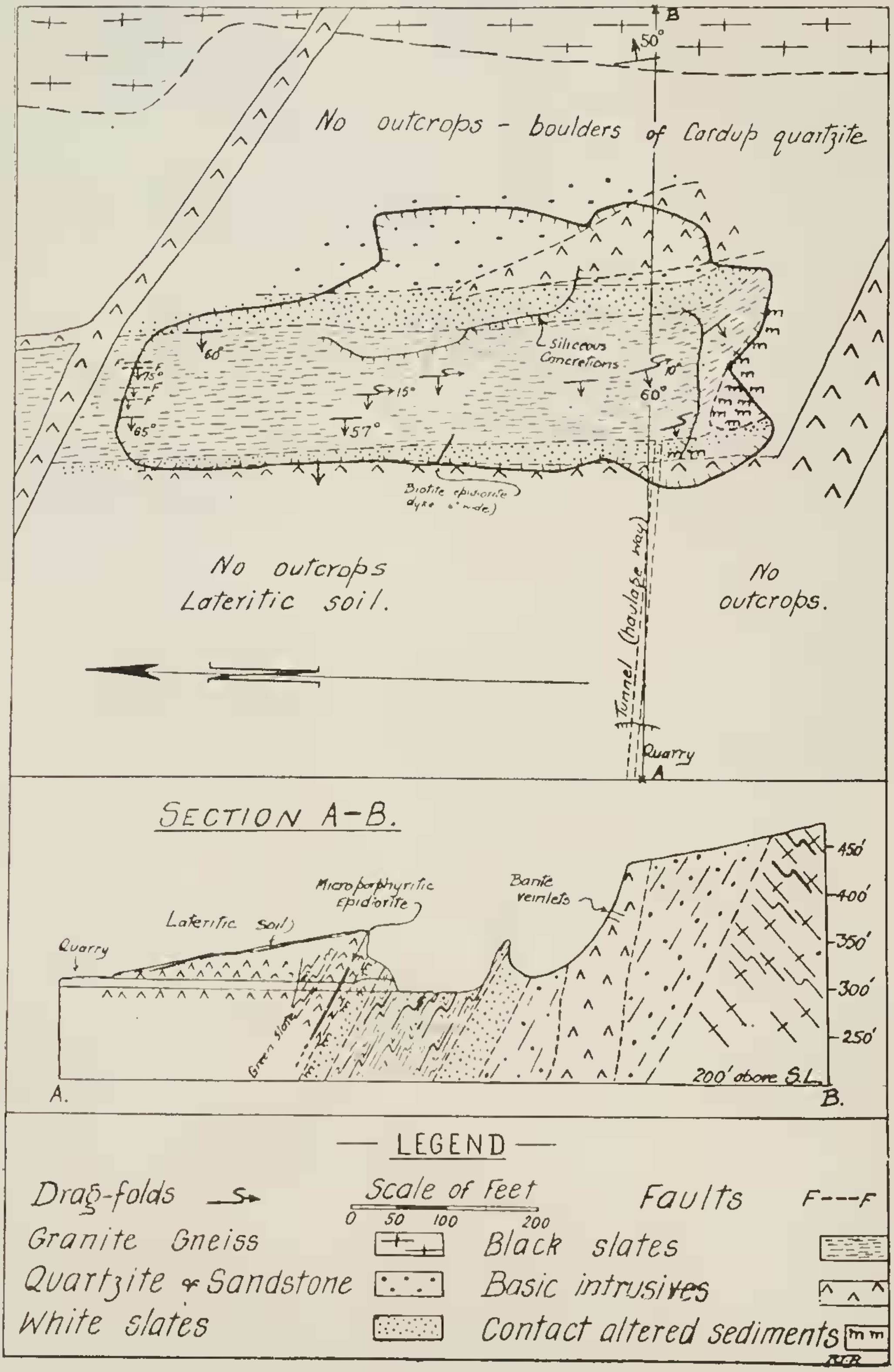

Figure 2.
Geological plan and section of the slate quarry, Armadale.

Minor structures (other than the graded bedding seen in several places on the Bedfordale Road) observed in the Cardup sediments were visible only in the slate quarry as other exposures are rather poorly developed. A detailed survey of the quarry was made for dragfolding, minor faulting and fracture cleavage and the results are shown in figure 2 (plan and section of the slate quarry). The drag-folds indicate that the beds to the west have moved *up* and over the beds to the east, i.e., that the slates in this quarry form the western limb of a normal anticline. A close examination across the black carbonaceous slate band at the south end shows that the dragfolds are directed in the same direction right throughout the band thus precluding the possibility of isoclinal folding in these rocks. All of the dragfolds observed pitch to the south at 10° to 15°. The bedding planes of the dragfolded slates show a distinct set of slickensides (Harnisch) which strike E. to W. normal to the axes of the dragfolds. Tests made of the roughness of the bedding surface in this direction indicate that the beds to the west have moved up and over the beds to the east.

The fracture cleavage is rather poorly developed in these rocks but where present is constant in strike (parallel to the bedding) and dip (almost vertical) throughout the quarry. In the northern wall of the quarry there are a number of small faults developed which are generally parallel to the fracture cleavage and along which movements up to 6 inches have been observed. All of these small faults (which are either vertical or dip very steeply to the west) are of reversed character and indicate upthrusting from the west (as deduced from the curvature, due to dragging, of the bedding planes in the vicinity of the faults).

It will be seen that all of these minor structures are closely related and almost certainly developed by the same movement, viz., a movement causing the western beds to be moved up and over the beds to the east. There are therefore two possible interpretations possible for these minor structures:—

(i) That these beds form the western limb of an anticline which pitches flatly to the south

or

(ii) That there has been upthrusting from the west, the sediments having been upthrust over the granitic gneisses lying to the east.

Considering the structural features of the Cardup sediments in conjunction with the structures in the band of fine grained granitic gneisses adjoining them to the east we see that they appear to be to some extent complementary, the gneisses forming the east limb of an anticline, the sediments forming the west limb of the same anticline. Forman (1937, p. xxiv.) considers that the gneisses may represent portions of the Cardup sediments which have suffered granitisation and it has been suggested to me (in discussions with Mr. H. A. Ellis) that in the Armadale Area the gneisses and sediments form part of a single structural unit (an anticlinal fold) which at the time of folding consisted entirely of sedimentary rocks of the Cardup Series, but which has since suffered partial granitisation, all of the rocks lying to the east of the axial plane of this anticline having been granitised and those to the west remaining unaffected by the granitising solutions which came from the east. Detailed field mapping, especially in connection with the field relations of the quartz veins, appears to indicate that the gneisses antedate the sediments, whereas the granitisation theory suggested by Forman (loc. cit.) requires that the Cardup sediments should be older than the granitic gneisses. The petrological evidence regarding the relative age of the gneisses and sediments and the possibility of granitisation of the Cardup sediments is discussed in the next section of this paper.

III. PETROLOGY.

(A) *The older hybrid gneisses and the associated xenoliths.*

These rocks are best exposed in the Roads Board quarry and most of the material described below came from this locality. Since the material forming the xenoliths has largely controlled the character of the hybridised granitic gneiss it will be described first.

Amongst the xenoliths three distinct types of material can be seen, thus:—

(i) *Quartz xenoliths.*

These are fragments up to four or five inches in diameter, mostly smaller. The quartz is clear and coarsely crystalline and under the microscope is seen to be an allotriomorphic mosaic of irregular shaped grains with crenulate boundaries. No signs of original clastic structure are visible and the large grains show only very slight strain shadows. Minute gas-liquid inclusions are very abundant. This material may have originated either from a quartzite or from quartz veins. It has contributed a considerable amount of what would at first sight appear to be primary (magmatic) quartz of the gneiss, for the size of the xenolithic quartz bodies varies down to the order of 5 mm. diameter.

(ii) *Epidote-muscovite xenoliths.*

These xenoliths occur in fragments up to four inches diameter. The rock is massive, very fine grained and consists of a fine mesh of small muscovite flakes with idioblastic tablets of highly birefringent epidote uniformly and abundantly dispersed throughout. The epidote is present to the extent of about 30 per cent. of the rock. In places remnants of untwinned (?) plagioclase (with the refringence approximately the same as that of canada balsam) crowded with sericitic inclusions are present. This rock appears to have resulted from the alteration of a basic plagioclase rock which must have been closely associated with the rocks from which the next group of xenoliths were derived.

(iii) *Hornblende-epidote-biotite hornfels xenoliths.*

Xenoliths of this type, which are dark greenish to black in colour, are the most abundant type and have exerted considerable control on the character of the hybrid gneiss, having contributed most of the ferromagnesian content of that rock. Rocks of this type appear to be rather constant in character wherever noted and are best developed in the Roads Board quarry. They are fine even grained, with no trace of any directed structure, the structure being coarse hornfelsic. Under the microscope the rock is seen to consist of a decussate aggregate of biotite and hornblende associated with granular aggregates of epidote. Irregular grains of magnetite are scattered uniformly throughout the rock, and apatite, in stout euhedra to 0.5 mm. diameter, is abundant.

The biotite and hornblende are closely associated. The biotite is a brownish-green, practically uniaxial variety with $\beta = 1.637$ and in all of the slices examined is considerably in excess of the bluish-green amphibole which occurs in well shaped prisms with irregular terminations, towards which the biotite is idioblastic. The amphibole has pleochroism, X brownish-green, Y brownish green, Z green (slightly bluish) and absorption $X < Y > Z$. The extinction $Z \wedge c$ is 18° and the optical character -ive. In several specimens a blue-green amphibole with X light yellow-green, Y olive green, Z bluish-green, absorption $X < Y < Z$ and $Z \wedge c = 17°$, is idioblastic towards the biotite. It occurs in elongated prisms, often in clusters with the long axes of individual prisms subparallel.

The epidote occurs in patches with an aggregate structure, made up of a mesh of tiny euhedral prisms, with which is associated some brownish-green biotite (in much smaller flakes than in the biotite-hornblende areas). The epidote is practically colourless and brightly polarising pistachite, although some fine granular zoisite appears to be present in the granular aggregates. These epidotic areas appear to represent a replacement of original calcic plagioclase.

In one specimen (19209)* the original structure of the rock can be seen by an examination of the slice under very low magnification—it is that of a coarse grained rock with plates to 4 mm. diameter of blue-green amphibole (now partially replaced by biotite aggregates) and felspar (now completely replaced by epidote) and it has undoubtedly originated from a coarse grained basic igneous rock. This is supported by the presence of skeletal plates of magnetite (fig. 3c) which appear to have been derived from ilmenite plates.

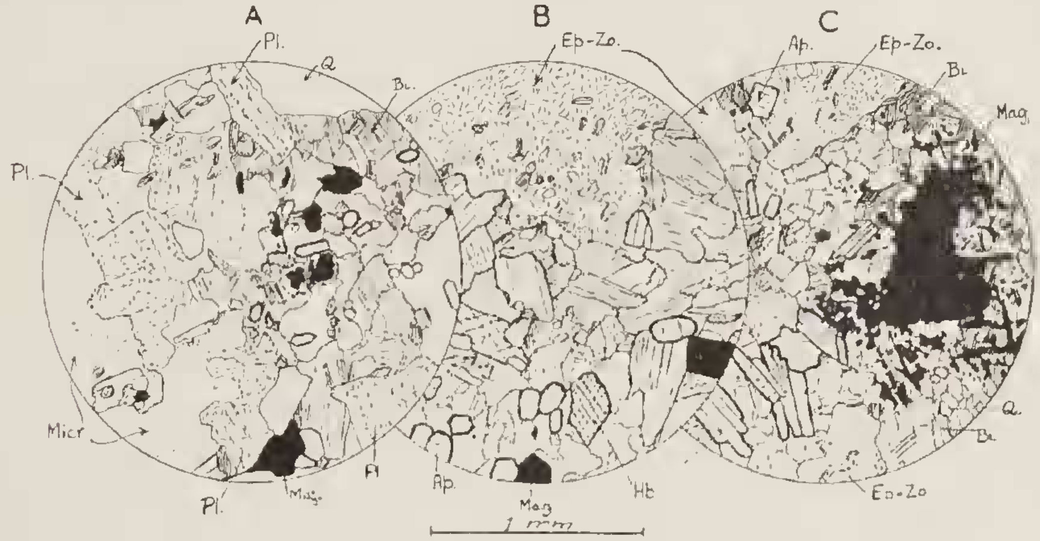

Figure 3.

A. Hybridised granite gneiss—showing basic clots consisting largely of greenish brown biotite, with magnetite and apatite. The granitic portion consists of an allotriomorphic granular aggregate of microcline (Micr), turbid plagioclase (Pl) and quartz (Q).

B. Basic xenolith—coarser variety of hornblende-biotite-epidote hornfels showing occurrence of epidotic aggregates (Ep-Zo) in distinct areas (originally plagioclase crystals). Shows also the decussate structured aggregates of biotite and hornblende (Hb), with magnetite and apatite (Ap) euhedra.

C. Basic xenolith—finer grained variety of hornblende-biotite-epidote hornfels, showing segregation of epidotic minerals in patches and large skeletal plate of magnetite (after ilmenite).

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* Catalogue number, Geology Dept., University of Western Australia.

Apatite is remarkably abundant and builds well shaped stout prisms which are idioblastic towards all the other constituents—it appears to have been introduced during the process of granitisation to which these basic rocks have been subjected. Magnetite and pyrite, scattered uniformly (the latter very sparsely) throughout the rock are the only other accessories.

An analysis made of this type yielded the result shown in Table I., column 1.

TABLE I.

	1.	2.
SiO	40·09	66·52
Al_2O_3	14·01	13·22
Fe_2O_3	6·05	4·99
FeO	14·42	3·29
MgO	4·34	0·58
CaO	9·89	2·84
Na_2O	0·46	3·45
K_2O	3·78	2·95
H_2O+	1·97	0·50
H_2O-	0·07	*Nil*
CO_2	0·08	0·03
TiO_2	2·76	0·66
P_2O_5	1·24	0·10
MnO	0·38	0·15
BaO	*Nil*	0·53
FeS_2	0·77	0·07
Fe_7S_8	0·02	*Nil*
Cr_2O_3	*Nil*	*Nil*
V_2O_3	0·03	0·04
SO_3	*Nil*	*Nil*
	100·36	99·92

Analyst: C. R. Le Mesurier.

1. Hornblende-epidote-biotite hornfels (19483), xenolithic in hybrid gneiss, Roads Board quarry, Armadale.
2. Hybrid gneiss (19482), rock enclosing the xenolith from which analysis 1 was made, Roads Board quarry, Armadale.

The composition of the basic xenoliths is peculiar, the most striking feature being the low silica and magnesia and the high figures for the iron oxides and potash. From the texture of the rock it appears to have been originally a medium grained basic igneous rock such as a gabbro although the FeO/MgO ratio is rather high. It must be borne in mind, however, that this rock has suffered considerable change, the original pyroxene having gone over to biotite, involving a loss of silica, magnesia, and lime and an addition of potash and alumina—the chemical evidence then supports the suggestion that these rocks were originally basic igneous types. There has been a marked concentration and fixing of P_2O_5 in these xenoliths. No rocks have been noted amongst the Cardup Series which could possibly be related in any way to the xenolithic masses in the hybrid gneisses.

The *hybridised gneiss* itself is a medium grained, well banded mesocratic rock. The dark bands which produce the gneissic appearance are composed largely of material similar to the basic xenoliths described above. Interbanded with this material are leucocratic bands of pale flesh coloured felspar closely associated with quartz and a pale greenish slightly epidotised felspar—in places the flesh coloured felspar is present as augen.

Under the microscope the most pronounced feature is the presence of dark clots, elongated parallel to the banding, which are made up of brownish green biotite, euhedral apatite, sphene, magnetite, and rare blue-green hornblende (fig. 3A). These clots are undoubtedly derived from the basic xenoliths which are so abundantly scattered through this gneiss (plate 2, fig. 1). The other constituents are considerably epidotised plagioclase (most abundant), clear microcline and quartz. The quartz is all slightly strained. Both quartz and microcline have enclosed the plagioclase.

An analysis of this rock is shown in Table I., column 2, and this indicates that there has been a considerable addition of both silica and soda to the original basic rock. As mentioned above some of the quartz of the hybrid gneiss may be xenolithic although the greater part, as seen from its relations with the introduced microcline, has undoubtedly been introduced during the granitisation process.

Read (1926, p. 165) has described the process of hybridisation of a granitic magma by ultrabasic material and his remarks apply equally well to the Armadale hybridised rocks. The basic xenoliths, in their high biotite content, are clearly hybrid types representing basic igneous material which has been permeated with potassic solutions from an intrusive granite. This granite, which represents the first period of granite intrusion in this area, was itself considerably hybridised by the incorporation of this basic hybrid and is now represented by the mesocratic hybridised gneiss described above.

(B) *The younger granite* (*Aplogranite*).

The aplogranites are leucocratic, medium to coarse grained (in places pegmatitic) rocks composed of quartz and felspar with practically no ferromagnesians. The texture is allotriomorphic granular and the constituents seen in thin slice are quartz, slightly perthitic microcline and oligoclase-albite with an occasional shred of greenish biotite. Both the microcline and finely twinned plagioclase are slightly dusted with inclusions and a noticeable feature is the frequent occurrence of myrmekitic structures in the plagioclase when it occurs in contact with microcline. Most of the quartz shows slight strain shadows.

This acid granite may have possibly been the intrusion which caused the earlier granitisation effects that have been noted above but in its field relations appears to belong to a distinctly later period of intrusion.

(C).—*The fine banded granitic gneisses* (forming the western edge of the granitic rocks).

In many respects these rocks are similar to the various gneisses and acid rocks of the Roads Board quarry, although no dark coloured xenolithic bodies have been found in them. Their structure varies from place to place, from finely banded granitic gneisses to almost massive granites in which no banded structures are visible. The massive structured rocks have a granitic texture and are made up of quartz, fresh microcline and slightly turbid oligoclase and so appear to be very similar to the aplogranites of the eastern half of the area. The finely banded gneisses contain quartz, microcline, oligoclase, clotted shreds of strongly pleochroic greenish-brown biotite and some muscovite, which appears to be developing from a turbid sericitised felspar. The microcline is perfectly fresh.

The exact relations of these rocks to the eastern gneisses are unknown. Petrologically they appear to be very similar although not so extensively hybridised and are only considered apart here because of their somewhat different strike. So far as could be seen there are no remnants of slate (see also under "quartz veins") in these granite-gneisses nor any development of minerals which would suggest the assimilation of argillaceous material by the intrusive granite. There is no chilled contact, the rocks being coarse grained right to the contact with the Cardup sedimentary series.

(D).—*The Cardup Series.*

(i) *The Sandstones:*

Near the contact with the granitic rocks the sandstones are medium grained grits and as the series is traversed in a westerly direction the average grain size diminishes. All types are very quartzose varying in colour from white to pale yellow green, where the rocks have been considerably epidotised. The white quartzites are composed almost entirely of slightly rounded to subangular equidimensional quartz grains to several mm. diameter in a finer grained quartzose groundmass containing occasional grains of epidote. Amongst the coarse grains there are occasional slightly rounded grains of clear microcline—these appear to be detrital and not introduced by later solutions and probably were derived from the erosion of the microcline bearing rocks to the east.

Close to the quartzite-granite gneiss contact on the Bedfordale road a peculiar light greenish epidotic quartzite is often developed. This rock is banded, made up of layers of epidotised quartzite (grit) and layers of darker greenish fine grained actinolite-epidote-quartzite with narrow irregular and lenticular bands of pale brownish cherty material. In some instances these cherty patches are small flattened ellipsoidal bodies, scattered throughout the comparatively coarse grit from which they are very sharply defined. The structure of these chert patches is fine grained hornfelsic and the constituents are mainly slightly turbid isotropic material with fine granular quartz, granular epidote and acicular (?) actinolite ($Z \wedge c = 16°$, pale greenish to colourless, not sensibly pleochroic, $\gamma = 1.644$). The origin of these peculiar cherty bands and lenticles is obscure but they appear to be original sedimentary structures which have later been contact altered. The most probable origin that suggests itself is that they represent small clay balls which have been flattened during the earth movements to which these rocks have been subjected. The presence of (?) actinolite suggests that these balls may have been to some extent calcareous.

The coarser gritty parts of these greenish quartzites are similar to the white quartzites with the addition of granular epidote which often occurs as angular grains moulded around the larger detrital quartz grains indicating that the epidote has been introduced after the formation of the original gritty sediment and was probably derived from the quartz dolerite intrusions which cut through the sediments in this locality.

(ii) *The slates.*

Two distinct types of slate are developed—their field relations have been discussed above.

(a) *The black slates*: these are finely bedded, dark grey to black in colour, different bands having varying content of graphitic material. The dominant constituent is fine fibrous sericite together with extremely fine granular weakly birefringent (?) quartz and black graphitic material. An interesting constituent is pale brownish green tourmaline, which occurs in minute idioblastic prisms to 0.05 mm. in length scattered sparsely, with random orientation, throughout the rock. It is strongly pleochroic, ω brownish green, ϵ colourless, and the refractive indices $\epsilon = 1.621$, $\omega = 1.649$, appear to indicate a member of the dravite-schorl group.

(b) *The white slates*: these rocks are made up almost entirely of fine fibrous sericite with a much smaller amount of pale brownish flaky biotite and minute clear grains of quartz. Minute idioblastic tourmaline prisms, similar to those in the black slates are distributed sparsely throughout the rocks (all of the slaty rocks examined contained this tourmaline none of which is detrital). Narrow darker coloured bands (up to 1 inch wide) occur in the white slates in places and these consist predominantly of pale brownish biotite with sericite in minor amount. The grain in these narrow bands is considerably coarser but this is largely an original feature and is not due in the main to recrystallisation as the quartz grains of such bands are markedly larger than in the white slate. The minute tourmaline prisms appear to be more abundant in these bands.

In some places near the western wall of the slate quarry, close to the albite-epidiorite, the white slate has a slightly knotted structure, the "knots" usually being small rectangular shaped plates (up to 4mm. x 4mm. x 1mm.) which consist of kaolin with small quartz grains distributed uniformly throughout. These porphyroblasts appear from their shape to be andalusites but careful search has not disclosed any relicts of this mineral. Their true character must therefore remain unknown but they appear to be the result of contact metamorphism of the slate by the nearby basic intrusion.

Joint planes in the white slates near the south-west corner of the slate quarry are coated with pale yellow earthy jarosite.

Other than the occasional thin dark bands and rare examples of the knotted slate, this group of white slates appears to be rather uniform in character. An analysis of a specimen from the west side of the slate quarry yielded the result shown in table II.

TABLE II.

	1.	2.	3.	4.	5.
SiO_2	65·22	61·63	58·38	50·10	50·00
Al_2O_3	16·71	16·33	15·47	25·12	24·14
Fe_2O_3	1·93	4·10	4·03	5·12	2·79
FeO	3·23	2·71	2·46	1·52	4·67
MgO	2·87	2·92	2·45	3·93	4·16
CaO	0·05	0·50	3·12	0·35	0·07
Na_2O	0·76	1·26	1·31	0·05	1·10
K_2O	5·98	5·54	3·25	6·93	8·63
H_2O+	2·12	3·24	3·68	6·82*	3·06
H_2O-	0·16	0·31	1·34	...	0·24
TiO_2	0·35	0·68	0·65	0·50	0·50
CO_2	0·05	0·41	2·64	...	0·07
P_2O_5	0·08	0·16	0·17	...	0·11
MnO	0·03	0·09	Tr.	...	0·04
BaO	0·11	0·06	0·05	...	0·15
FeS_2	*Nil*	0·04	...	...	...
Cr_2O_3	0·01	...	...	...	0·01
V_2O_3	0·03	...	...	...	0·04
SO_3	0·11	...	0·65	...	0·15
Graphite	0·05	*Nil*	0·81†	...	0·07
NaCl	*Nil*	...	...	...	..
(Others)	...	0·06	...	...	..
	99·85	99·98	100·46	100·44	100·00

Analyst: C. R. Le Mesurier.

* Ignition loss on material dried at 110°C. † Organic material.

1. White slate (19203), west side of slate quarry, Armadale.
2. Cambrian slate, Vermont (*U.S. Geol. Surv. Bull.* 591, p. 250).
3. Composite analysis of 78 shales (F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv. Bul'.* 770, 1924, p. 30).
4. Illite (fine colloid fraction), Ordovician shale, Gilead, Calhoun Co., Illinois (R. E. Grim, R. A. Bray and W. F. Bradley, "The micas in argillaceous sediments," *Amer. Min. Vol.* 22, 1937, p. 823).
5. Analysis of Armadale slate (of col. 1) with SiO_2 reduced to 50% and the other oxides recalculated to sum to 100, for comparison with analysis of illite (col. 4).

In this table the analysis of the Armadale slate is compared with that of a slate from Vermont, U.S.A. (col. 2) which it resembles very closely, and with the average of 78 analyses of shale (col. 3). The main features of the analysis are the high silica, alumina and potash, the two latter being a reflection of the high sericite content. Such features would be common in slates derived from illite rich clayey sediments (an analysis of illite is shown in table 2, col. 4 and is compared with that of the Armadale slate from which excess silica has been removed (col. 5), and although the potash content is high, it is quite normal and does not indicate that the rock has suffered any "granitisation."

(c) *More arenaceous types:* to the east the slates become more arenaceous and pass gradually into the normal sandstones. On the western side of the quarry, between the white slate and the albite epidiorite, there is a band of greenish more sandy slate. This band swings towards the east at the south end of the quarry. This rock is distinctly coarser textured and comparatively large rounded quartz grains are abundant—the only other constituent of note is a greenish brown biotite which appears to have developed during contact metamorphism of this band by the basic intrusive. Separation of the heavy minerals yielded only a few much worn and rounded zircons. At the south end of the quarry this greenish rock encloses several rounded boulders of granitic material which consist largely of a granophyric intergrowth of quartz and acid plagioclase. These "boulders" appear to be somewhat rounded and some doubt exists whether they are boulders or irregular granophyric intrusions, as they are traversed by narrow (¼-inch wide) veinlets of quartz which appear to pass through both the boulders and the enclosing green sandy sediment. I incline to the view that they are boulders and that the associated veinlets are similar to the quartz veins developed in the Cardup Series (which are described under "quartz veins" below).

(iii) *Contact metamorphism of the Cardup sediments.*

Considering first the arenaceous rocks close to the contact with the granitic rocks—the main contact metamorphic effects have been the introduction of epidote and the development in certain narrow bands of acicular (?) actinolite—the latter are in radiating aggregates and appear to result from the thermal metamorphism of a slightly calcareous rock but whether this alteration is due to intrusion by the granite or to intrusion by the quartz dolerite dykes is not clear—the introduction of the epidote was most likely effected during the intrusion of the doleritic rocks.

In the slates lying farther to the west there has been some new mineral development :—

(1) The development of the kaolinic knots which seems to be closely related to the greenstone intrusions.

(2) The presence of idioblastic tourmaline in all the slaty rocks of this area is interesting—this mineral may have been introduced from granitic intrusions, from the basic intrusives (Agrell, 1939, p. 333, has described the development of dravite in adinoles and considers that the boron was introduced from nearby albite dolerites) or may have developed from the boron contained in the original unmetamorphosed sediments. Goldschmidt and Peters (1932) have shown that the boron content of clay sediments is often sufficient to bring about crystallisation of tourmaline when these sediments suffer dynamic metamorphism and that it is not necessary to look to later acid intrusives for the origin of the boron. The absence of tourmaline from the rocks immediately adjacent to the granite and its occurrence in the slates some distance away seems to suggest that it was not derived from that source. It is possible then that the tourmaline was introduced from the basic igneous rocks but more probable that it resulted from the crystallisation of original constituents of the argillaceous sediments from which the slates were derived.

(3) The development of biotite and chloritoid. Biotite has undoubtedly been formed during the metamorphism of the slaty rocks as it is often well developed on the fracture cleavage surfaces. It is well developed in small pale brownish flakes in the slates from the slate quarry which are close to greenstone intrusions but is absent farther to the north (along the Bunbury Road) where the slates are some distance from the intrusive dykes. This points to the development of the biotite being due to contact alteration consequent upon the intrusion of the basic rocks. Specimens from the haulage tunnel leading out from the south-west corner of the slate quarry afford information regarding the contact alteration of the Cardup sediments—the rocks in this tunnel consist of slates and sandstones which have been intruded by a chlorite-albite epidorite sill and then later by a quartz-dolerite dyke, both of which have in some measure affected the sediments. The rocks (together with brief descriptions) encountered in this tunnel are (see fig. 4) :—

From east end to 45 feet in*—*normal slates* showing development of small flakes of pale brownish biotite.

From 45′ to 49′ in—*chloritoid slate*—this is the normal slate (similar to that from 0′ to 45′) with a development of small chloritoid porphyroblasts, at first rare and then becoming more abundant towards the west. The chloritoid porphyroblasts are well formed but have been replaced by penninite with extremely weak birefringence (almost isotropic with very weak ultra blue interference colours), positive elongation and marked pleochroism X pale yellow green, Y = Z deep green. At first sight these small porphyroblasts appear to be chloritoid but the pleochroism and orientation are those of penninite. There is little doubt, however, that they were originally chloritoid. This is the only place where this mineral has been found in the area and it is of interest as it seems to fix the period of intrusion of the chlorite-albite epidiorite as more or less contemporaneous with the earth movements affecting the Cardup Series. Chloritoid is generally regarded as a stress mineral—in the present instance it is clearly related in some way to the epidiorite sill as it decreases in amount away from that body.

---

* All measurements are from the east end of the tunnel and have been measured along the north wall.

It appears most probable that it developed during the earth movements which affected the Cardup Series while these rocks were still at elevated temperatures following the intrusion of the greenstone sill.

From 49′ to 53′ in—*biotite-quartz hornfels*—these rocks are hornfelsed argillaceous sandstones. They are fine grained, dark green in colour and under the microscope are seen to be made up of rounded quartz grains with interstitial flaky pale brown biotite with some pale green chlorite and sericite.

From 53′ to 90′ in—*chlorite-albite epidiorite sill* (described in a later section) with a narrow intrusion of a microporphyritic epidiorite between 57′ and 58′.

From 90′ to 99′ in—contact altered *sandy slate* similar to that between 49′ and 53′ except that it is much finer grained and apparently less altered, the biotite being in much smaller flakes.

From 99′ to 109′ in—*quartz-biotite-actinolite hornfels* similar to the actinolite bearing hornfelses developed in the arenaceous sediments nearer the granite contact (described in the section dealing with the Cardup sandstones).

From 109′ to 311′ in—*uralitised quartz-dolerite.* At 311′ there are several small irregular bodies (? veins) of coarse grained quartz (which under the microscope shows considerable cataclasis).

From 311′ to the west end—greenstone, probably the chlorite-albite epidiorite but the rocks here become too weathered for exact determination.

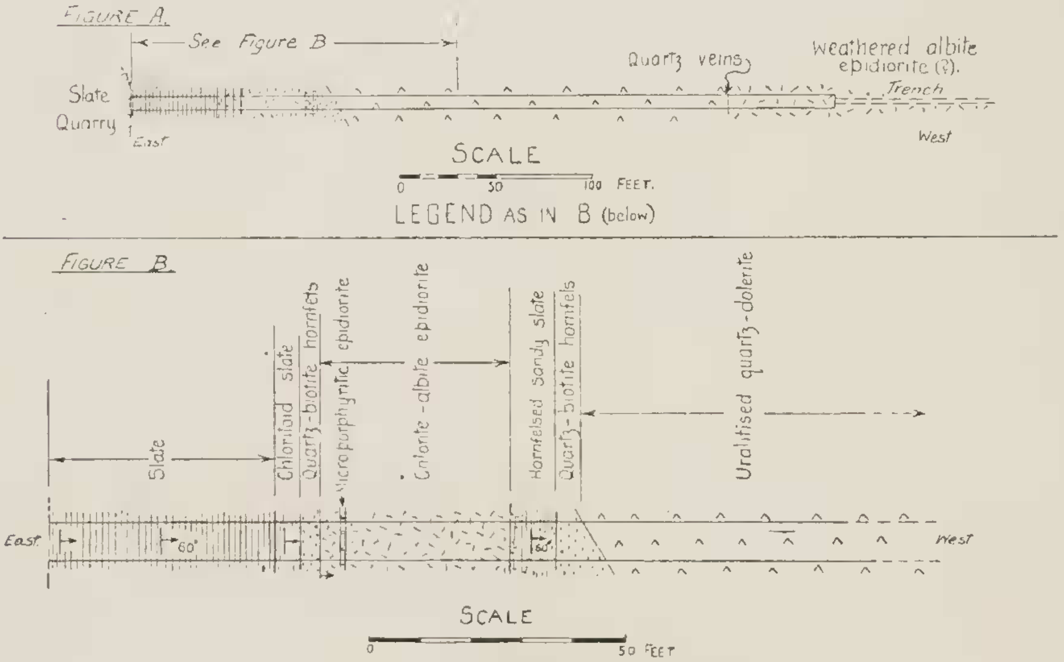

Figure 4.

A. Geological sketch plan of the tunnel leading out from the south-west corner of the slate quarry, Armadale.

B. Enlargement of geological plan of east end of the tunnel from the slate quarry, showing the relations of the Cardup sediments, the chlorite-albite epidiorite sill and the later quartz dolerite dyke (note the narrow intrusion of microporphyritic epidiorite into the chlorite-albite epidiorite sill).

The section exposed in this tunnel indicates that the Cardup sediments have been contact metamorphosed over limited distances by both the chlorite-albite epidiorite and the later quartz-dolerites. It also indicates that the development of the epidote-actinolite-quartzite noted near the granite contact is a contact effect due to the quartz-dolerites and not to the granitic rocks.

(E). *The basic intrusives of post-Cardup age.*

The following types have been recognised:—

(i) *Chlorite-albite epidiorites.*

This type has been noted in one place only, viz., in a sill like intrusion into the slates in the west wall of the slate quarry. This body is itself intruded by a narrow "sill" (12 inches wide) of a microporphyritic epidiorite, which is described below.

The chlorite-albite epidiorite is of interest because it can undoubtedly be correlated with the porphyritic albite epidiorite (referred to as albite porphyrite by Esson, 1927, p. 6) which occurs at various localities (Wungong, Cardup, Whitby Falls and Mundijong) extending some 15 miles to the south along the Darling Scarp. The rock at Armadale is not porphyritic but its texture and mineralogical composition (both of which differ considerably from the normal quartz-dolerites) are similar to those of the rocks from the areas to the south.

The Armadale rock is medium. even grained and almost indistinguishable in hand specimen from the uralitised quartz-dolerites. It consists of a plexus of clear albite prisms (figure 5B) with interstitial aggregates of chlorite, uralite and biotite together with some turbid epidotic material and a little leucoxene. The chlorite forms a fine grained mesh enclosing patches of green uralitic amphibole and occasional flakes of pale greenish-brown biotite. It is a pale greenish prochlorite, very slightly pleochroic and almost isotropic (with very weak anomalous colours)—the optic character is neutral and the refractive index $\beta - 1.633 \pm .002$. This mineral agrees with the chlorites of the low grade epidiorites described by Wiseman (1934, p. 360.) The albite is fresh (although slightly dusted with inclusions and penetrated by acicular amphibole) and thus differs considerably from the epidotised plagioclase of the other basic igneous rocks of the area.

The analysis of this rock is recorded below:—

TABLE III.

SiO_2	47·08
Al_2O_3	14·78
Fe_2O_3	1·32
FeO	13·80
MgO	7·45
CaO	4·24
Na_2O	3·10
K_2O	1·03
$H_2O +$	3·89
$H_2O -$	0·22
TiO_2	2·49
P_2O_5	0·41
MnO	0·31
BaO	*Nil*
Cr_2O_3	*Nil*
FeS_2	0·14
	100·26

Analyst: R. T. Prider.

Norm.	
Or	6·12
Ab	26·20
An	18·35
C	1·84
hy	26·49
ol	9·47
mg	1·86
il	4·71
ap	1·01
py	0·14

Chlorite-albite epidiorite (20532), 78 feet from east end of tunnel, Slate quarry, Armadale.

The most outstanding features of this analysis are the low CaO and the considerable Na_2O content which indicate that the felspar prior to metamorphism was moderately rich in the albite molecule and that the rock was approaching a spilitic type. It certainly differs considerably from the later quartz-dolerites which contain a much higher proportion of lime (see Table IV.). An unusual feature is the excess of alumina and the appearance of corundum in the norm—this excess of alumina is no doubt contained in the chlorite and its presence may be due to slight contamination of the epidiorite by the aluminous slates which is has intruded.

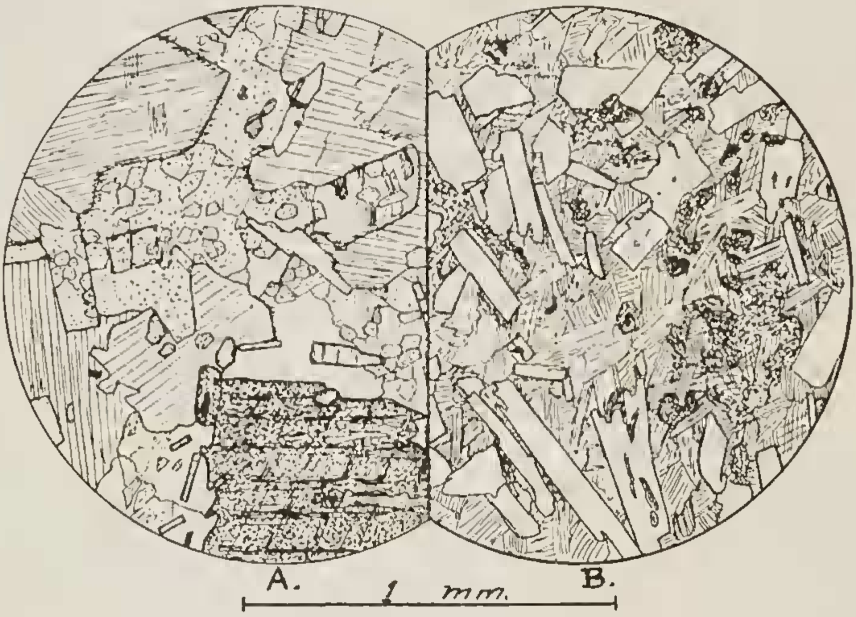

Figure 5.

The basic intrusives.

A. Uralitised quartz dolerite, showing subophitic relation of uralite and turbid plagioclase (dotted), plates of leucoxene after ilmenite and angular areas of end phase quartz with rods of apatite.

B. Albite epidiorite, showing clear laths of albite in a ground of biotite, uralitic amphibole and turbid epidotic material.

The field relations of this rock are shown in figure 4. Consideration was given, on a previous page, to the contact metamorphism effected by this sill on the Cardup sediments, and, in the development of chloritoid, it was considered that the post Cardup earth movements took place shortly after the intrusion of the chlorite-albite epidiorite. This rock then is a low grade epidiorite showing a grade of metamorphism comparable with that of the associated sediments. The quartz-dolerite group (to be described presently) appears to belong to a later period of intrusion, as a microporphyritic epidiorite (described under (iii) below) which is considered to be genetically related to the quartz-dolerites is intrusive into the chlorite-albite epidiorite.

(ii) *Uralitised quartz-dolerites.*

Rocks of this group form the bulk of the post Cardup intrusions and all are very uniform in character. Variations in granularity dependent on the position in the dyke are noticeable but the mineralogical composition remains constant with the exception that the end phase quartz and micropegmatite are somewhat more abundant in the central parts of the dykes than on the edges.

The characteristic ophitic to sub-ophitic texture of the quartz-dolerites is always developed, although somewhat obscured by uralitisation and epidotisation (figure 5A). A typical specimen from the large dyke striking south-east from the Roads Board quarry is a greenish, medium even grained rock, which consists of pale green uralite, epidote, zoisite, leucoxene, quartz and minor accessories including a little brown hornblende, biotite and apatite. A relict ophitic relation is visible between the uralitic amphibole plates and the zoisitic aggregates replacing plagioclase prisms, the only other noticeable textural feature being the angular patches of quartz and micropegmatite (in which the felspar is represented by turbid zoisitic aggregates).

The uralite is the most abundant constituent, occurring in plates up to 1 mm. diameter. It is a pale greenish fibrous variety with weak pleochroism, X very pale greenish (almost colourless), Y pale green, Z pale green, absorption $X < Y = Z$, extinction $Z \wedge c = 16^\circ$ and (—) 2V large. It is often dusted with magnetite inclusions. No relict pyroxene is visible, nor has any been noted in any of the basic intrusive rocks of this area. In the vicinity of the quartz and micropegmatite areas the uralite shows a further change to pale green, weakly pleochroic, optically positive chlorite and more rarely to brownish hornblende.

The plagioclase is represented by granular aggregates of zoisite, epidote and fine granular plagioclase. Ilmenite has been replaced entirely by fine granular leucoxene which occurs in areas up to 1½ mm. diameter in which the skeletal structure of the original ilmenite is preserved. Occasionally the leucoxene is recrystallised to sphene, which occurs in rounded grains with central iron ore inclusions.

The quartz and micropegmatite areas in this rock, up to ½ mm. diameter, are similar to those of the normal quartz-dolerites except that the felspar is replaced by fine granular zoisite. These quartz and micropegmatite areas are penetrated by slender prisms of apatite. In specimens from the centre of this same dyke the micropegmatite areas vary in size to 1½ mm. diameter and the presence of brownish hornblende in its vicinity is more noticeable.

TABLE IV.

	1.	2.	3.	4.
SiO_2	48·83	49·13	49·22	50·52
Al_2O_3	13·46	13·13	12·62	13·76
Fe_2O_3	2·88	3·65	3·16	3·87
FeO	10·29	8·95	11·09	8·50
MgO	8·03	7·64	6·42	5·42
CaO	11·95	11·84	10·59	9·09
Na_2O	1·32	1·72	1·86	2·42
K_2O	0·50	0·16	0·30	0·96
$H_2O +$	1·39	1·72	2·24	1·51
$H_2O -$	0·08	0·04	0·12	0·76
CO_2	...	...	*Nil*	0·58
TiO_2	1·24	1·27	2·00	2·39
P_2O_5	0·07	0·14	0·09	0·26
MnO	0·18	0·15	0·33	0·16
BaO	*Nil*	...	*Nil*	0·03
FeS_2	Tr.	0·45	0·22	0·06 (S)
Cr_2O_3	0·08	...	Tr.	Tr.
V_2O_3	...	...	Tr.	0·05
	100·30	99·99	100·26	100·34
Analyst :	R. T. Prider.	R. T. Prider	—	—

TABLE IV.—*continued.*

Norms.			
Q	1·86	3·48	4·14
Or	2·78	1·11	1·78
Ab	11·00	14·15	15·74
An	29·19	27·52	25·18
di	23·86	24·88	22·15
hy	23·07	18·60	20·12
mt	4·18	5·34	4·58
cm	0·22	...	...
il	2·28	2·43	3·80
ap	0·34	0·34	0·34
py	...	0·45	0·22

1. Uralitised quartz-dolerite (20464), near Roads Board quarry, Armadale.
2. Uralitised quartz dolerite, Toodyay, Western Australia. (Prider, 1938, p. 95.)
3. Epidiorite (uralitised quartz dolerite), Bickley, Western Australia. (Clarke and Williams, 1926, p. 173).
4. Quartz dolerite (average of 6 analyses), Whin Sill, Northern England. (Holmes and Harwood, 1928, p. 530.)

These rocks are therefore best described as completely uralitised quartz-dolerites. An analysis of the typical specimen described above is given in Table IV. where it is compared with other uralitised quartz-dolerites from Western Australia and with the average composition of the Whin Sill.

It will be seen that the analyses of the three Western Australian quartz dolerites are very similar, So far as is known, these rocks all belong to the same period and are all intrusive into the granitic rocks of the Darling Range. In comparison with the normal quartz dolerites (as exemplified by the Whin Sill rocks), they are somewhat richer in iron, lime and magnesia and correspondingly slightly poorer in silica and soda.

(iii) *Microporphyritic epidiorite.*

The occurrence of this rock as a narrow intrusion into the chlorite-albite epidiorite has been noted above. The rock is greenish and extremely fine grained and has a microporphyritic texture with equidimensional phenocrysts of uralite (? after pyroxene) up to ½ mm. diameter (often aggregated to form glomerophenocrysts), and tiny plagioclase laths to ½ mm. long, in a fine grained ground of plagioclase, epidote, zoisite, uralite and pale brownish biotite. The fibrous uralite of the phenocrysts is very pale in colour with similar pleochroism to that in the quartz dolerites, and it shows patchy alteration to biotite. No original pyroxene is visible. This type appears to be closely related to the quartz dolerites, of which it is a fine grained porphyritic representative.

(iv) *Biotite epidiorites.*

This type of rock has been noted in two places only—as a narrow dyke (four feet wide) intrusive into the hybridised gneiss in the Roads Board quarry and as a narrow dyke (10 inches wide) intrusive into the slates in the Slate quarry. The occurrence in the Roads Board quarry appears to be an offshoot from the larger uralitised quartz dolerite to the south-east (described above) but this is by no means certain. It is definitely intrusive into the hybrid gneiss, for it truncates the banding sharply and cannot be one of the basic xenoliths (which it resembles mineralogically).

It is a fine even grained greenish rock showing little, if any, sign of schistose structure. Under the microscope it is seen to consist of a fine allotriomorphic granular aggregate of brownish-green biotite, plagioclase, epidote (and zoisite) and pale green amphibole with accessory leucoxene (after small ilmenite grains) and quartz in small angular grains.

The biotite is a brownish green variety with pleochroism X pale yellow-green, Y = Z deep brownish-green, and absorption $X < Y = Z$. The axial angle is very small (almost uniaxial) and $\beta = 1.628 \pm .002$. In parts of the rock it occurs in clotted aggregates with a decussate structure, appearing to be either xenolithic or replacing ferromagnesian phenocrysts.

The amphibole is a pale greenish, slightly pleochroic uralite with $Z \wedge c = 16°$. The plagioclase has mostly been replaced by granular epidote and zoisite, but rare small laths of untwinned albitic plagioclase remain.

This rock, in its high biotite content, differs considerably from the uralitised quartz dolerites of the area. An examination of specimens collected from across the dyke showed that the edges are very rich in biotite, which is present to the exclusion of the amphibole, the rock consisting of biotite, epidote (and zoisite) and minor amounts of leucoxene, albite and quartz. The biotite here is in flakes to 0.25 mm. diameter, which is large compared with flakes in the central parts of the dyke, and is often aggregated into clots. At three inches in from the edge the structure is the same with clotted biotites in a ground of biotite, epidote, zoisite and amphibole with accessory leucoxene and quartz. In the centre of the dyke the grain is slightly coarser and the main ferromagnesian is the pale bluish-green amphibole which is in excess of the brown-green biotite. Angular grains of quartz are also more abundant. The mineralogical variation throughout the dyke may be shown by the following estimates of the mineralogical composition of the different rocks examined (figures quoted are volume-percentages) :—

	Edge of dyke.	3in. in from edge.	Centre.
Biotite	65	50	22
Amphibole	*Nil*	15	40
Epidote + zoisite ...	30	30	30
Leucoxene	1	1	1
Albite + quartz ...	4	4	7

An analysis of the specimen from 3 inches from the edge of the dyke yielded the result shown in Table V. It will be seen from this table that chemically this rock appears to be more closely related to the chlorite-albite epidiorite than to the quartz dolerite, the only difference between analyses 1 and 2 being in the alkalies, the biotite epidiorite being exceptionally rich in potash while in the chlorite-albite epidiorite soda is considerably in excess of the potash—it may be noted here however that certain specimens of the chlorite-albite epidiorite that were examined showed considerably more biotite than the specimen analysed.

Wiseman (1934, p. 401) has noted the production of biotite in the peripheral parts of an epidiorite sill at Loch Fyne, Scotland, and he considers that both chlorite and biotite have been produced during the shearing of the epidiorite mass during which process some potash has been introduced by freely circulating solutions thus leading to the formation of biotite. In the Armadale rock there is but little evidence of shearing but the biotite rich peripheral parts of the dyke are similar to the occurrence described by Wiseman. This dyke is intrusive through a considerable mass of the biotitic hornfels in the south-eastern corner of the quarry and may have picked up some potash from this source. However the complete absence

TABLE V.

	1.	2.	3.
SiO_2	48·88	47·08	48·83
Al_2O_3	16·18	14·78	13·46
Fe_2O_3	3·06	1·32	2·88
FeO	11·00	13·80	10·29
MgO	6·87	7·45	8·03
CaO	4·79	4·24	11·95
Na_2O	0·96	3·10	1·32
K_2O	5·32	1·03	0·50
H_2O+	1·24	3·89	1·39
H_2O-	0·33	0·22	0·08
TiO_2	1·49	2·49	1·24
P_2O_5	0·14	0·41	0·07
MnO	0·16	0·31	0·18
BaO	0·14	*Nil*	*Nil*
Cr_2O_3	0·03	*Nil*	0·08
FeS_2	n.d.	0·14	n.d.
	100·59	100·26	100·30
Analyst :	R. T. Prider.	R. T. Prider.	R. T. Prider.

1. Biotite epidiorite (20188), three inches in from edge of dyke, Roads Board quarry, Armadale.
2. Chlorite-albite epidiorite, Armadale. (Quoted from Table III.)
3. Uralitised quartz-dolerite, Armadale. (Quoted from Table IV.)

of amphibole from the edges of this dyke seems to indicate that it has been entirely replaced by biotite and it seems most probable that end phase potassic solutions have been active in these narrow dykes. There is no definite evidence to say to which of the other types of basic intrusive this type is related but the chemical data indicate that it is most probably related to the chlorite-albite epidiorite.

The rock from the narrow dyke in the slate quarry is very similar to that occurring on the edges of the dyke described above with the exception that it is somewhat schistose and very rich in biotite.

(F).—*The quartz veins.*

In the granitic gneisses there are two sets of quartz veins as described in the first section of this paper. So far as can be seen by microscopical examination these veins are similar—they appear to be replacement bodies in shear zones in the granitic rocks, similar to those noted in the Darlington Area (Clarke and Williams, 1926, p. 174). Specimens from the north-west striking veins 300 yards south-west from the Narrogin Inn, show that in places it is a quartz sericite rock which in places has small ironstained cubic cavities from which pyrite has weathered. One specimen from here contained a considerable amount of a fine acicular mineral which is developed in numerous small radiating clusters. These small needles are colourless, have straight extinction and negative elongation and appear to be dravite similar to that described by Simpson (1931, p. 141) from various quartz veins in the granitic rocks of the Darling Range.

The large quartz outcrop near the south end of the area may be taken as representative of the north striking veins. At the surface it appears to be a coarse grained white quartz in some places containing darker coloured strings of slaty material which under the microscope is seen to consist largely of sericitic mica. This dark coloured material, xenolithic in the vein quartz, was analysed and the analysis is shown in table VI., and it will be seen that it is very similar to the analysis of muscovite. A noticeable feature of the analysis is the high baryta content, and the presence of very little SO_3 indicates that it is not in the form of barite but must be in the mica. No barite was visible in the thin sections examined. Floaters of this sericitic material can be traced for some distance in a northerly direction and this appears to be a shear zone in the granitic rocks along which replacement quartz veins have been formed. The other possibility is that this band of sericitic material is an infolded portion of the Cardup slates along which quartz has been introduced. Comparing the analysis of the sericitic material with that of the white slate (table VI, col. 4) the main difference is seen in the amount of SiO_2. If silica is added to the sericite schist to bring it to 65.22% and the remaining oxides recalculated to sum to 100 (col. 3) there is seen to be a close agreement, the main differences being in the higher FeO and MgO in the slate (due to chlorite), the different proportions of the alkalies and the higher BaO content of the sericite schist (this seems to be a significant feature as the BaO in the sericite schist must be in the mica—in this connection it is interesting to note the comparatively high BaO content of the hybridised gneiss in table I.). It must be noted that the products of sericitisation of alkali felspar are similar to those accumulating in certain fine grained argillaceous sediments (especially illitic clays) so that a comparison of these analyses, which are both of highly sericitic rocks, does not convey any real information regarding the origin of the sericite

TABLE VI.

	1.	2.	3.	4.
SiO_2	47·54	43·37	65·22	65·22
Al_2O_3 ...	29·01	33·19	19·22	16·71
Fe_2O_3 ...	3·59	1·95	2·38	1·93
FeO	1·33	1·00	0·88	3·23
MgO ...	1·53	1·36	1·01	2·87
CaO	*Nil*	*Nil*	*Nil*	0·05
Na_2O ...	0·09	1·03	0·06	0·76
K_2O	10·25	10·17	6·79	5·98
H_2O+ ...	4·42	7·74 Loss on ignition.	2·93	2·12
H_2O— ...	0·06		0·04	0·16
CO_2	0·03	...	0·02	0·05
TiO_2 ...	0·85	0·33	0·56	0·35
P_2O_5 ...	*Nil*	...	*Nil*	0·08
MnO ...	0·12	...	0·07	0·03
BaO ...	1·01	...	0·67	0·11
Cr_2O_3 ...	0·02	...	0·02	0·01
V_2O_3 ...	0·13	...	0·08	0·03
SO_3 ...	0·07	...	0·05	0·11
				0·05 (Graphite)
	100·05	100·14	100·00	99·85

Analyst: H. P. Rowledge. C. R. Le Mesurier.

1. Sericite schist (19481), (dark patches xenolithic in quartz vein, from which all vein quartz has been removed), near Bedfordale Road, Armadale, *Anal.* H. P. Rowledge.
2. Muscovite, Bamle, Norway. (*Amer. Jour. Sc., vol.* 24, p. 259, 1939).
3. Analysis 1 with SiO_2 made up to 65.22% and the remaining oxides recalculated to sum to 100.
4. White shale, Armadale, Western Australia (quoted from Table II.).

schist. The presence of similar quartz-sericite rocks associated with the north-west system of quartz veins, which in view of their disposition in the field, cannot be regarded as infolded portions of the Cardup slates, would appear to indicate that both groups ot veins are of similar origin, i.e., replacements along shear zones. This is supported by the absence in the vicinity of the quartz blow at the south end ot the area of other remnants of the Cardup series, for if the slates were infolded then a considerable portion of the more arenaceous sediments underlying them must also have been infolded—no trace of these remains and the evidence is overwhelmingly against the possibility that this band represents an infolded portion of the Cardup slates.

A similar quartz vein in the granitic gneiss near the contact with tho sediments of the Cardup Series has been noted near Kelmscott. This occurrence is exposed in a small road cutting on a road leading east from the townsite. The exact position of the sediment-granite contact cannot be located as exposures are very weathered and poor. The slaty Cardup rocks are exposed in several small pits and, as at Armadale, dip steeply to the west. The granite contact lies approximately 200 feet east of these pits and about 200 feet east of the contact there is a quartz vein which strikes 200° and dips steeply to the east. It is bordered by sheared material which at first sight appears to be slate but when closely examined is seen to have a "lensy" structure and not the well bedded character of the slate. Although the material was too weathered for microscopic examination it appears to be a sheared granitic rock rather than the Cardup slate and the occurrence is remarkably similar to that at Armadale. The shear zone in the Kelmscott occurrence is approximately 10 yards wide.

Returning to a consideration of the large quartz blow—in places it has a banded appearance where the quartz has been injected along the schistosity planes of the sericite schist (plate 2, fig 2A). Below the surface, the vein is represented by a quartz muscovite rock not unlike a fine grained greisen, the muscovite here having been recrystallised. The massive quartz of the vein has all been strained (plate 2, fig. 2B) and is, in this respect, similar to that of the north-west group. This straining may have been effected during the movements which tilted the Cardup Series.

All the evidence available, both chemical and petrological, suggests that the north-west and north groups of quartz veins in the gneissic rocks are similar in character and were formed during the same period along shear zones which are developed in a regular pattern and that these veins were subjected to post-crystallisation stress.

Turning now to a consideration of the quartz veins in the Cardup slates—no actual vein in situ was seen in this area, although the presence of heaps of quartz fragments in the slate quarry indicates its presence. Campbell (1910, p. 29) describes these quartz masses as "bunches of quartz veins up to 18 inches diameter." They are probably similar to a larger occurrence of vein quartz in the slates at Cardup, some miles to the south (Clarke, 1930, map on p. 166). The quartz from the Armadale slate quarry is fine, even grained, white, and under the microscope is seen to be an equigranular aggregate of allotriomorphic grains (Plate 2, fig. 2C) which have not suffered any post-crystallisation stress. This vein material therefore appears to have been formed at a later period than the quartz veins in the granitic rocks (which all show stress effects). The veins in the slates appear to be closely related to a thin seam of siliceous concretions which are developed along the east wall of the lower bench in the quarry (fig. 2)—these concretions occur as flattened ellipsoidal bulges averaging 9 inches diameter, projecting from the bedding surface. They have a concentric structure, are cut by numerous intersecting joints and are composed almost entirely of fine grained quartz. The texture is allotriomorphic granular, similar to that of the quartz veins but much finer in grain (average grain size of concretions 0.03 mm. diameter while that of the veins averages 0.15 mm.). Although exposures here do not permit a definite pronouncement that the concretions and quartz veins are genetically related it appears probable that the vein material represents a more complete segregation and coarser crystallisation of the silica than the concretions and that both have been formed by the same process. It is hoped that further light will be thrown upon the origin of these veins by work now in progress by Mr. B. Thomson in the Cardup area. One point however is clear—that the quartz veins in the slates are later than those in the granitic rocks and have not been strained during the movements which affected the Cardup Series.

Other veins:—In the east wall of the slate quarry some very thin veinlets of barite were noted in the highly weathered rock which appears to be one of the basic intrnsives. This occurrence is interesting since it throws some light on the origin of the barite-fluor veins in the Cardup Series at Cardup (Clarke, 1930, map on page 166)—it indicates that the barite veins are later than the basic intrusives and were therefore probably derived from the greenstone magma rather than the granite magma. It is interesting to note here that Sweet (1930, p. 258) considers that the barite and fluor bearing veins of the north of England are genetically related to the quartz dolerites of the Whin Sill.

On the south side of the Bedfordale Road (outside the area described in this paper) quartz veins containing small amounts of galena and sphalerite have been found. These occurrences have not been closely examined but they appear to be similar to the silver-lead deposits of Mundijong (Esson, 1927) which are closely associated with a porphyritic albite epidiorite (albite porphyrite of Esson) which is similar to the albite epidiorite from Armadale. The suggestion is put forward here that these silver-lead veins and barite-fluor veins are genetically related to the basic magma rather than to the granitic magma.

IV. CONCLUSIONS.

(a) *The age of the Cardup Series.*

The evidence presented by the quartz veins (both in their field relations and petrology) indicates that the granitic rocks are older than the Cardup sediments. This conclusion is supported by a number of other facts:—(i) that the Cardup Series is a normal erosion sequence and is constant in character along the strike; (ii) that nowhere have the "granitising" solutions been seen to traverse the basal beds of the series nor have any apophyses (such as pegmatites or quartz veins) been seen to pass into the sediments; (iii) that there are no remnants (xenoliths) of the sedimentary series in the gneisses, the only remnants being of older basic igneous rocks; (iv) that no variation in character of the gneiss across the strike, such as would be expected if a series of varying lithology were granitised, has been noted, and (v) the slight contact metamorphic effects noted in the Cardup Series are due to the basic intrusions. Indeed, the only evidence that has been found which in any way favours a pre-granite age for the Cardup Series, lies in the presence in the slates of small amounts of idioblastic tourmaline, which as described above, may equally well be explained as due to crystallisation of components of the original sediment during the earth movements which tilted the Cardup Series.

The position of the Cardup Series in the Pre-Cambrian succession of Western Australia (as deduced from all the evidence available in this area) is therefore later than the final granite intrusions and earlier than the basic igneous intrusions of the Nullagine period (late Pre-Cambrian). I have recently had occasion to examine a collection of rocks from the Stirling Range Series and from the evidence at present available these rocks appear to belong to the same period as the Cardup Series—the field relations of the Stirling Range Series have been investigated by Professor E. de C. Clarke and further details regarding these rocks will be given in a future paper.

(b) *The Darling "Fault" Scarp.*

The area described above includes one of the numerous flat spurs which extend out from the present line of the scarp. If the Darling Scarp is a fault scarp then the fault should be situated somewhere in the vicinity of the tip of these projecting spurs. Movements of the magnitude required to produce a downthrow to the west of several thousands of feet (as required to explain the structure of the coastal plain) should surely be reflected in the comparatively weak slates forming these spurs. Observation of all the minor structures in the slates of the Armadale area indicates in every instance, that the western side has been pushed up and over the rocks lying to the east and appears to negative the possibility of any large faults with a downthrow to the west in the vicinity. The structures are consistent with an extensive downwarp to the west involving a tilting of the Cardup Series to the west and minor upthrusting along the eastern margin of the downwarp. If this be the case (and it will only be proved or disproved by close investigation of the structures in the Cardup Series all along the face of the scarp) then the Darling Scarp, which is one of the most pronounced physiographic features of south-western Australia, must be an erosion feature due to differential erosion of a monoclinal fold rather than a fault structure.

(c) *The Geological History of the Area.*

The geological history of the area, from the evidence presented in the foregoing pages, may be summarised as follows:—

1. Period of granitisation during which pre-existing basic rocks were permeated by granitic emanations and the hybrid gneisses produced.
2. Period of granite intrusion (aplogranite).
3. Earth movements, causing development of shear zones and joint pattern in the granitic gneisses, followed by the formation of the quartz veins in the gneisses.
4. Deposition of the Cardup sediments.
5. Formation of an extensive downwarp parallel to the present Darling Scarp and some distance to the west, involving upthrusting along the eastern margin, development of fracture cleavage in the slates and tilting of the sediments to the west.
6. Intrusion of albite epidiorite sill into Cardup Series, probably contemporaneous with (5).

7. Intrusion of the quartz dolerite series of dykes consequent upon earth movements affecting the Cardup Series.
8. Formation of barite veins as end phase effects of the basic intrusions (galena-sphalerite-quartz veins also probably belong to this period).

End of Pre-Cambrian.

9. Downwarping continuing and sediments being constantly deposited in the depression—the only evidence regarding this long period of geological time being the two thousand feet (at least) of Cainozoic sediments which underlie the coastal plain and cover up all intervening formations. Block faulting may have taken place (as suggested by Jutson, 1935, p. 469) during the uplift of the Western Australian plateau in late Miocene times but differential erosion of hard rocks of the plateau and the soft rocks to the west of the scarp seems capable of explaining the present physiographic features.

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EXPLANATION OF PLATE 2.

Figure 1—

Hybrid gneiss from the Roads Board quarry, Armadale, showing xenolithic character of the gneiss. The xenoliths are of biotite-hornblende-epidote hornfels (dark coloured) and epidotic material (light coloured). The banded character of some of this gneiss is seen in the top left hand side of the boulder. Quartz xenoliths are present (the coin is lying on one) but they are indistinct in the photo. The clinometer gives the scale.

Figure 2.—Photomicrographs of quartz veins.

A. Sericitic rock from shear zone in gneiss, with secondary veinlets of quartz (from large quartz blow near the Bedfordale Road). Ordinary light x 40.

B. Strained quartz from the same locality as (A). The entire field (and almost all of the slide from which this photo was taken) is part of the same crystal. The strain pattern is interesting, consisting of subparallel lines along which actual granulation has taken place arranged obliquely to the direction of "slicing" or gliding shown by the strain shadows. Nicols crossed x 40.

C. "Vein" quartz from the slate quarry. Occurs as masses in the slates. Shows unstrained character and even granular mosaic structure. Nicols crossed x 40.

Plate 2.

Figure 1.

A B C

Figure 2.